Differential Frequency Hopping (DFH) Modulation for Underwater Acoustic Communications and Networking

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LONG-TERM GOALS

The goal of this project is to mature existing DFH modulation and demodulation algorithms for use in the doubly-spread (time and Doppler) underwater acoustic channel in order to provide the ability for multiple users to seamlessly communicate in the bandwidth-limited acoustic channel.

OBJECTIVES

The primary technical objective of this effort is to realize theoretical DFH performance in the doubly spread underwater acoustic channel. To do so, we need to develop demodulation schemes that are robust to various aspects of the environment. Variations in water depth, bottom type, sound speed profile, and source/receiver location can provide for wide ranges of multi-path interference (resulting in time spread). Different wind and surface wave conditions in combination with platform motion can result in varying degrees of Doppler spreading. The developed algorithms must work well across the range of conditions that will be encountered in real-life scenarios.

Within the doubly-spread underwater acoustic channel, we wish to increase throughput without penalty to the inherent interference and collision tolerant properties of the waveform. This includes channel access by multiple users sharing the same frequency band (and even the same hop set) and the same time interval.

APPROACH

This project involves a close collaboration between BAE Systems and APL/UW. The project employs simulation studies for which BAE Systems generates DFH transmit sequences for multiple users and APL/UW uses those signals as the transmit waveforms in Sonar Simulation Toolset (SST) simulations. The team collaborates on processing of the simulated signals, assessment of the algorithm's performance, and design of enhancements to improve performance for use in the underwater channel. We also provide waveforms for at-sea experiments performed between FY07 and FY09. The approach is to provide DFH waveforms to be transmitted simultaneously by multiple sources, and then analyze the data to assess performance and improve algorithm design. The measured data also serve as a validation tool for our simulation environment.

The technical approach for the waveform and demodulation environment proceeds in a method we have successfully employed on similar programs: a simulate, test, and develop cycle, followed by additional development cycle(s) with experimental and simulated data. Quantitative evaluation of network availability, jammer and multi-user interference rejection, LPI, LPD, throughput, and other performance measures guide development, both using the simulation outputs and the collected data.

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14. ABSTRACT

The primary technical objective of this effort is to realize theoretical DFH performance in the doubly spread underwater acoustic channel. To do so, we need to develop demodulation schemes that are robust to various aspects of the environment. Variations in water depth, bottom type, sound speed profile, and source/receiver location can provide for wide ranges of multi-path interference (resulting in time spread). Different wind and surface wave conditions in combination with platform motion can result in varying degrees of Doppler spreading. The developed algorithms must work well across the range of conditions that will be encountered in real-life scenarios.

Within the doubly-spread underwater acoustic channel, we wish to increase throughput without penalty to the inherent interference and collision tolerant properties of the waveform. This includes channel access by multiple users sharing the same frequency band (and even the same hop set) and the same time interval.

15. SUBJECT TERMS

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WORK COMPLETED

Responsibility for the related project at APL/UW transitioned smoothly from Warren Fox to Luca Cazzanti at the beginning of 2008's work. The transition provided an opportunity to clarify our strategy in finer detail, including publication objectives.

We started 2008's effort by developing an auto-synchronizing, single-user decoder and running it on 60s simulation files (~3600 symbols) for both soft and hard bottom compositions. We found good performance with a single-hydrophone receiver for the soft bottom with up to eight users and good performance for the hard bottom with up to two users. The negative impact of multi-path is compounded with multiple users as the channel becomes crowded with the long-duration multi-path energy of interfering transmitters.

We amended our signal set defined for SPACE07 for transmission at the Rescheduled Acoustic Communications Experiment 2008 (RACE08). These signals were successfully transmitted, received, and demodulated. The transmitted signal set was composed of six different user configurations:

1. Single user, no jammer
2. Two users, no jammer
3. Four users, no jammer
4. Single user, jammed with a slow chirp across the band (appears as a tonal jammer within any hop interval)
5. Two users, jammed with the same signal as configuration #4
6. Three users, jammed with the same signal as configuration #4.

The data rate for each user is 68 bits per second in the 4 kHz band between 9 and 13 kHz. The six signal configurations supported development and test of two processing enhancements: a multiple access mitigation technique that can operate in ignorance of the other users' presence and code used, and a fading mitigation technique that also does not require any additional information. These enhancements do not require the use of training symbols or a channel probe, and can be repeated as needed due to channel variability without cooperation from the transmitter. APL/UW also used this data set for development of an SST model that correctly simulates the channel.

We also created a signal for transmission at GLINT08 that was successfully received. This signal is a single-user scenario, but includes moving transmitters and receivers, which will support development of more Doppler-resistant processing of DFH signals. We abandoned work on the AUVFest 2007 signals due to confusion with the defined scenario.

We participated in the ONR Acoustic Communications Programs Review at the Woods Hole Oceanographic Institution in June 2008. In September 2008 we presented portions of this work, including the auto-synchronizing decoder, results from the SST simulations, and results from the RACE08 data processing at OCEANS 2008 in Quebec, QC. In July 2008 we expanded our submission for the OCEANS 2008 proceedings to include the processing enhancements and related results for submission to the autonomous underwater vehicle applications in undersea warfare theme issue of the *U.S. Navy Journal of Underwater Acoustics.*

We started 2009's effort by demodulating the GLINT08 data. Our hopes for a difficult dataset to support development of movement-robust demodulation techniques were opposed by the overall success of the baseline demodulator.

We re-examined the RACE08 dataset and excluded from our results receptions where another team's signal was transmitted, or where only ambient noise was recorded (for these trials we failed to synchronize to a DFH signal, and reported 50% BER in our previous results).

We amended our signal set for SPACE07 and RACE08 for transmission at SPACE08. These signals were successfully transmitted, received, and demodulated. The transmitted signal set was composed of three different user configurations: single user for 30s, two users for remaining 30s; three users for 60s; and four users for 60s. Because we used a wider bandwidth (~8kHz) we had a higher data rate than in RACE08, transmitting up to 6835 symbols each reception file. This dataset supported development of a multi-channel receiver and comparison between this receiver and an adaptive beamformer preceding our single-channel receiver, taking advantage of the spatial diversity represented in this data collection.

We participated in the ONR Acoustic Communications Programs Review at the Woods Hole Oceanographic Institution in June 2009. In May 2009 we presented portions of this work, focusing on experimental results, at the Acoustical Society of America meeting in Portland, Oregon. Our submission to the ONR Journal of Underwater Acoustics was accepted for publication with revisions. We completed the revisions and resubmitted the paper for publication.

RESULTS

Auto-synchronizing Decoder

The auto-synchronizing decoder works by decoding the reception at all possible sample delays (equal to the number of bins) over a short duration (4× (the number of bins) symbols – for instance, if there are 64 bins, the synchronization happens over 4×64=256 hop intervals.). It then evaluates the accumulated metric at the end of that short duration. The sample delay yielding the best metric value is then used for demodulating the rest of the sequence. If the metric value (output along with the demodulated bit sequence) is observed to fall below a threshold, the synchronization procedure can be repeated. The demodulation then proceeds by decoding each user's sequence at the user's sample delay.

To describe the decoder, we first define the following notation:

- $S_\tau(f, T)$ is the value at frequency bin f at hop interval T for the periodogram S calculated at sample delay τ;
- $f_T = G_k(f_{T-1}, b_T)$ shows the operation of the code G for the user k: the frequency transmitted at the current hop f_T is a function of the frequency transmitted at the previous hop f_{T-1} and the bit in the current hop interval b_T
- $m_k(T)$ is the output metric sequence for the user k as a function of hop interval T;
- $m_k(T,f)$ is the intermediate metric state for the user k as a function of hop interval T over the vector of trellis states f.

For each destination state f, $m_k(T,f) = S_\tau(f, T) + \max(m_k(T-1,f_0), m_k(T-1,f_1))$ in which f_0 and f_1 are defined by $f = G_k(f_1, 1)$ and $f = G_k(f_0, 0)$. The decision to take the maximum of these two is lossless: if the two hypotheses were carried forward through the transmission, any metric value downstream of the smaller of these two options could never exceed the corresponding metric value downstream of the greater one. The output metric sequence $m_k(T)$ is selected as the intermediate metric state with the highest metric value over the states f. This selection can be made d hops after the current hop interval T without increasing the error rate, in which d is the depth of the user code G.

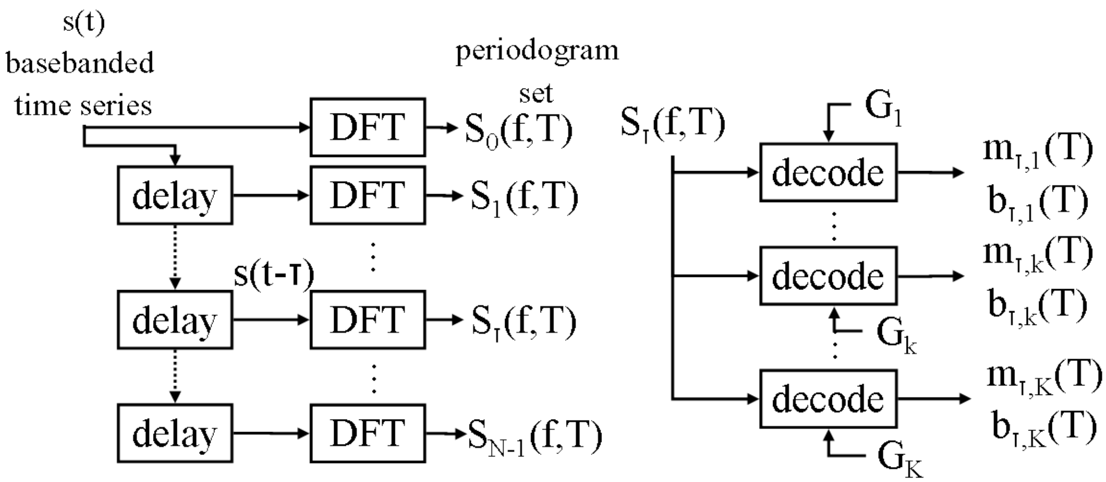

Figure 1: Block diagram of the auto-synchronizing decoder

This demodulation, in conjunction with acquisition that needs no training symbols, gives us an efficient, auto-synchronizing, single-user demodulator. In GLINT08 there were 50 DFH transmissions. This demodulator has zero errors for 35 of these. Of the remaining 15, 7 have less than 1% BER and 8 have between 1% and 10% BER. As this test includes drifting and moving transmitters, the eight worst receptions will support future development of a more Doppler-resistant DFH receiver.

Processing Enhancements

The enhancement made to the baseline efficient, auto-synchronizing, single-user demodulator combines two processing techniques: a multiple access interference mitigation technique and a channel fading mitigation technique. The multiple access interference mitigation technique is based on work by Chen et al. It works by subtracting contributions from previous and following hop intervals in each bin. Since the users are asynchronous, interfering users appear both in the hop interval of interest and in the hop intervals immediately preceding and following. That is, in addition to the ordinary periodogram $S_\tau(f, T)$, we also compute two additional periodograms at the same sample delay τ: $S_{before}(f, T)$ and $S_{after}(f, T)$ using the offset Tukey windows shown in Figure 2.

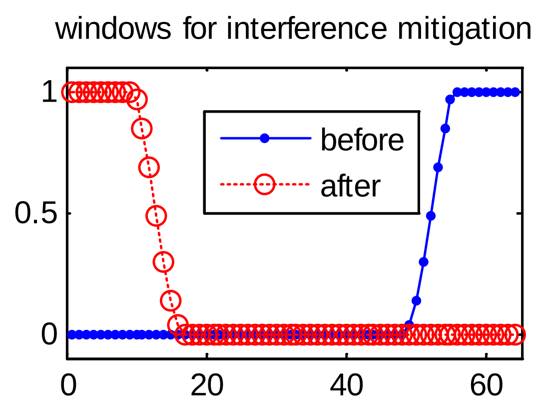

Figure 2. Windows used for multiple access mitigation

[graph: The window used for the 'before' periodogram has a value of 1 in the last quarter of the window, and smoothly transitions to 0 in the rest of the window. The window used for the 'after' periodogram has a value of 1 in the first quarter of the window and smoothly transitions to 0 in the rest of the window. The windows capture a portion of the time series closest to the current hop interval.]

Then, we decode a periodogram with the multiuser interference suppressed: $S_\tau\ (f,\ T)\ -\ S_{before}\ (f,\ T\text{-}1)\ -\ S_{after}\ (f,\ T\text{+}1)$. This mitigation procedure does not require the receiver to know that other users are present; therefore, no parameters such as sample delay or transmitter configurations such as trellis code need to be known or estimated for any user not of interest.

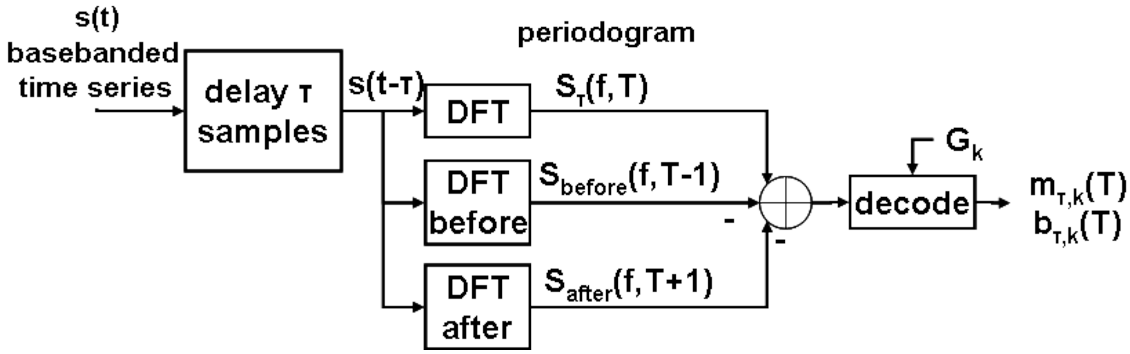

Figure 3: Block diagram describing the Multiple Access Interference mitigation

We mitigate the effect of frequency-selective fading by flattening the spectrum after forming the periodogram, but before decoding. This is accomplished by computing an average power in each bin, and then weighting the bins across the band so that the resulting spectrum has the same power in each bin. The weighting can be updated as a function of time if needed as the channel changes, with no coordination required with the transmitter.

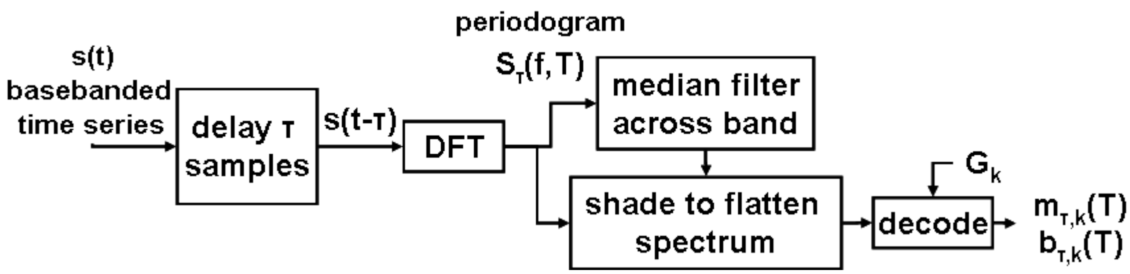

Figure 4: Block Diagram describing the channel fading mitigation

Our single-hydrophone results from the RACE08 data set are summarized in the following table, expressing our performance in terms of the proportion of error-free transmissions:

RACE08 - Single Element

	400 m from Source Array				**1000 m from Source Array**			
Config	Baseline	fading mitigated	MAI mitigated	both mitigations	Baseline	fading mitigated	MAI mitigated	both mitigations
Single User	100%	100%	98%	98%	66%	81%	79%	89%
User 1 of 2	45%	60%	58%	63%	20%	25%	23%	31%
User 2 of 2	85%	92%	94%	95%	57%	66%	69%	70%
User 1 of 4	2%	5%	9%	20%	1%	5%	5%	11%
User 2 of 4	16%	39%	43%	63%	38%	42%	58%	63%
User 3 of 4	38%	49%	48%	68%	35%	38%	49%	58%
User 4 of 4	28%	57%	62%	76%	34%	43%	47%	56%

The single hydrophone furthest from the bottom (located in the mid-watercolumn) is used at both receiver locations. While the overall performance of the single-hydrophone receiver is generally good,

the table of results from the RACE08 data shows a peculiar trend: for multi-user scenarios, the user transmitting from transmitter type ITC1007 (user 1 of 2, and user 1 of 4) has worse performance than the user transmitting from transmitter type AT12ET. This trend can be explained by examining the transmit power level characteristics of the two types of acoustic sources. The ITC1007 transmitter is between 1dB and 7dB lower in power than the AT12ET transmitter in the band of interest (9-13kHz). This power diversity led to errors on the quieter user because the single-user demodulator does not implement a multi-user detection (MUD) algorithm to account for the mutual interference caused by the other users. The fading mitigation and MAI mitigation procedures are described in our 2008 report. We see that the single-user trials have perfect performance at 400m range for the baseline receivers, and the penalty for the mitigation processing is small. For the multi-user trials, the mitigation processing improves performance, often increasing the proportion of perfect trials by an order of magnitude. Note that the multiple users are uncoordinated: they have different trellises, but interfere in both time and frequency.

In 2009 we developed a non-coherent multiple channel combining procedure to take advantage of the spatial diversity available in the collected datasets. Synchronization (as described above) is performed on each channel independently. One of the output products of the synchronization is a bit sequence. These are cross-correlated between the channels to be combined. If the peak cross-correlation falls below a threshold, the inferior channel is dropped. Otherwise, the two spectrograms are aligned and summed incoherently before demodulation is performed.

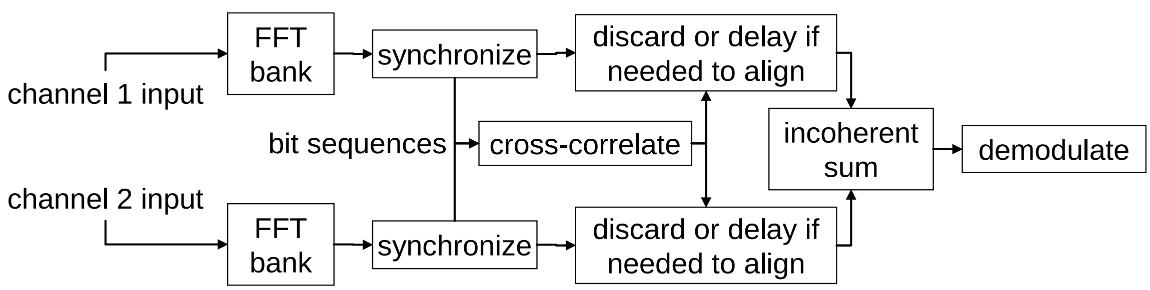

Figure 5: Block diagram of the non-coherent multi-channel combining

The performance of this multi-channel receiver is shown on the SPACE08 dataset, in terms of the proportion of receptions that were error-free, in conjunction with the channel fading mitigation described above, for the six receiver arrays used.

SPACE08 - Multi-element

	southeast 60m				southwest 60m			
	single channel		two channels		single channel		two channels	
	baseline	fading mit.	baseline	fading mit.	baseline	fading mit.	baseline	fading mit.
user 1 of 2	92%	92%	92%	92%	77%	74%	100%	99%
user 2 of 2	32%	32%	84%	85%	44%	46%	57%	56%
user 1 of 3	60%	70%	73%	80%	6%	20%	79%	88%
user 2 of 3	0%	0%	52%	69%	0%	2%	74%	80%
user 3 of 3	0%	11%	47%	83%	8%	18%	92%	95%
user 1 of 4	23%	43%	93%	94%	1%	4%	80%	95%
user 2 of 4	1%	11%	46%	73%	0%	1%	31%	57%
user 3 of 4	0%	0%	5%	25%	0%	0%	5%	23%
user 4 of 4	0%	0%	43%	69%	3%	5%	57%	80%
	southeast 200m				**southwest 200m**			
	single channel		**two channels**		**single channel**		**two channels**	
	baseline	**fading mit.**	**baseline**	**fading mit.**	**baseline**	**fading mit.**	**baseline**	**fading mit.**
user 1 of 2	52%	46%	99%	99%	12%	22%	94%	98%
user 2 of 2	36%	33%	28%	29%	4%	9%	96%	95%
user 1 of 3	0%	0%	95%	95%	0%	0%	91%	94%
user 2 of 3	3%	8%	80%	88%	0%	0%	63%	88%
user 3 of 3	30%	44%	88%	98%	11%	38%	57%	63%
user 1 of 4	4%	4%	93%	96%	0%	2%	51%	95%
user 2 of 4	0%	0%	32%	71%	0%	0%	34%	54%
user 3 of 4	4%	6%	7%	42%	0%	6%	18%	75%
user 4 of 4	15%	24%	70%	85%	6%	24%	54%	93%
	southeast 1000m				**southwest 1000m**			
	single channel		**two channels**		**single channel**		**two channels**	
	baseline	**fading mit.**	**baseline**	**fading mit.**	**baseline**	**fading mit.**	**baseline**	**fading mit.**
user 1 of 2	51%	67%	75%	81%	35%	50%	77%	83%
user 2 of 2	17%	25%	35%	56%	15%	25%	53%	75%
user 1 of 3	18%	47%	45%	61%	33%	56%	68%	76%
user 2 of 3	3%	5%	9%	47%	0%	3%	14%	52%
user 3 of 3	0%	3%	9%	48%	0%	0%	8%	38%
user 1 of 4	13%	33%	58%	90%	10%	23%	43%	83%
user 2 of 4	2%	8%	8%	46%	1%	11%	17%	50%
user 3 of 4	1%	5%	2%	14%	1%	6%	7%	26%
user 4 of 4	1%	6%	13%	23%	2%	7%	10%	24%

We see that the two-channel results, using the non-coherent multi-channel receiver, are uniformly better than the single-channel results, often increasing the proportion of error-free trials by an order of magnitude. In particular, see user 1 of 3 at 200m range: we have no error-free trials with the single-channel receiver, but over 90% error-free trails with the non-coherent multi-channel receiver. The channel fading mitigation is compatible with the non-coherent multi-channel receiver, and further enhances our performance.

On the SPACE08 data, we also examine a coherent data-adaptive beamformer. We find the dominant eigenvector of the reception across the vertical aperture, and use those weights to beamform the channels into a single time series, which is then decoded with the baseline single-channel receiver. In this comparison, we only examine the single-user portion (first half) of user 1 of 2. Almost all of the receptions for this case are error free, so we report the number of trials that had any errors, for each array location.

	SE 60m	SW 60m	SE 200m	SW 200m	SE 1000m	SW 1000m
single-channel	7	0	1	2	37	29
eigen-beam	7	0	0	0	1	0

The benefit of coherent beamforming is most evident at 1km range, likely due to the increase in SNR. The number of trials with errors is small enough for the eigen-beam case that we can individually examine each trial to determine the cause of the errors. For the 7 trials with errors at 60m range, a known clock problem caused these trails to lose synchronization, for both receivers. The one trial with errors at 1km range is more interesting: its BER is 0.3% and examination of the time series shows three long episodes of bursty noise.

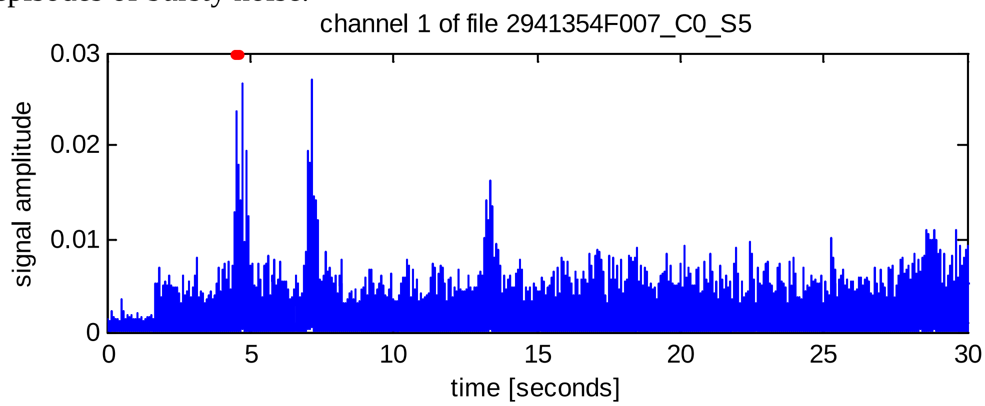

Figure 6: Single-user portion of channel 1 from SPACE08 file 2941354F007_C0_S5. Error locations are marked at the top axis of the plot with red dots. [Shows a time series 30s long with an average signal amplitude of 0.002, with three noise bursts with amplitudes greater than 0.01. The noise bursts are half a second in duration. The errors occur at the same time as the first (and longest) noise burst.]

The DFH signal can correct for errors less than or equal to its trellis depth in length. For the SPACE08 signal, the trellis depth is six symbols, or 0.05 seconds, so we are not surprised that the receiver's failure to resolve the symbols during this noise burst.

Overall, the power of the DFH waveform for reliable underwater acoustic communication has been shown on collected data, and enhancements improving the receiver's performance for this application have been demonstrated. Further improvements to the multi-channel processing show very promising results on more recently collected data, particularly for multi-user cases. This work continues into the follow-on contract. It can be briefly summarized as channelized non-coherent minimum variance distortionless response (MVDR) processing. These experiments, the processing employed, and their

results will be presented and discussed at the program review in May 2010, and ultimately included in the final report for the follow-on contract.

IMPACT/APPLICATIONS

As the utility of distributed underwater acoustic systems (including the deployment of AUVs) progresses in Naval applications, so too does the need for these underwater assets to communicate information between them. DFH's provision of the ability for multiple users to seamlessly communicate in the bandwidth-limited acoustic channel is critical. Efforts by an adversary to jam an undersea network can also be overcome by the use of DFH coding. This combination of features will allow Naval undersea networks and cooperative AUVs to function together in an efficient and robust manner.

TRANSITIONS

DFH transition opportunity exists both within ONR to programs such as the Persistent Littoral Undersea Surveillance Network (PLUSNet) and external to ONR to program offices that have responsibility for distributed undersea network systems (e.g. PEO IWS 5, Undersea Systems), undersea vehicles (e.g. PMS 403, Unmanned Undersea Vehicles), and communications (e.g. PMW 770, Submarine Integration). The transition potential for DFH coding is primarily a software consideration. Current underwater acoustic modem developers routinely implement regular FSK coding schemes. DFH coding would utilize the same acoustic bandwidth as the existing modems, but with specialized arrangement of the FSK "chips" on transmit, and specialized demodulation algorithms on receive.

RELATED PROJECTS

This program falls within the scope of the ONR 321US D&I *Signal Processing for Underwater Acoustic Communication Networks* effort. The program that is intimately coupled to our effort is APL/UW's *DFH Modulation for Underwater Acoustic Communications and Networking.* In this joint effort, BAE Systems is responsible for development of the waveform enhancements and the multi-user demodulation algorithm. APL/UW is responsible for the simulation activities. The two organizations are collaborating in the development of the equalizer and auto-synchronization algorithms.

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